The LHeC – Science and Status

Max Klein
University of Liverpool

for the LHeC+FCC-eh Study Group

DIS Workshop at Birmingham, 7th of April 2017

LHeC: $E_e=60$ GeV $E_p = 7$ TeV

FCC_eh: $E_e=60$ GeV $E_p = 50$ TeV

HE LHC: $E_p=12.5$ TeV

For references, please consult
lhec.web.cern.ch

LHeC CDR
arXiv:1206.2913
Road beyond Standard Model
LHC results vital to guide the way at the energy frontier

At the energy frontier through synergy of

hadron - hadron colliders (LHC, (V)HE-LHC?)

lepton - hadron colliders (LHeC ??)

lepton - lepton colliders (LC (ILC or CLIC) ?)
Framework of the Development

Following the CDR in 2012: Mandate issued by CERN:2014 (RH), confirmed in 2016 (FG)

<table>
<thead>
<tr>
<th>Mandate to the International Advisory Committee</th>
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<tbody>
<tr>
<td>Advice to the LHeC Coordination Group and the CERN directorate by following the development of options of an ep/eA collider at the LHC and at FCC, especially with:</td>
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<td>Provision of scientific and technical direction for the physics potential of the ep/eA collider, both at LHC and at FCC, as a function of the machine parameters and of a realistic detector design, as well as for the design and possible approval of an ERL test facility at CERN.</td>
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<td>Assistance in building the international case for the accelerator and detector developments as well as guidance to the resource, infrastructure and science policy aspects of the ep/eA collider.</td>
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Chair: Herwig Schopper, em. DG of CERN

LHeC has been a development for and initiated by ECFA and NuPECC
**International Advisory Committee**

“..Direction for ep/A both at LHC+FCC”

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
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<tbody>
<tr>
<td>Sergio Bertolucci</td>
<td>(CERN/Bologna)</td>
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<tr>
<td>Nichola Bianchi</td>
<td>(Frascati)</td>
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<td>Frederick Bordry</td>
<td>(CERN)</td>
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<td>Stan Brodsky</td>
<td>(SLAC)</td>
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<td>Hesheng Chen</td>
<td>(IHEP Beijing)</td>
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<td>Eckhard Elsen</td>
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<td>Andrew Hutton</td>
<td>(Jefferson Lab)</td>
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<td>Young-Kee Kim</td>
<td>(Chicago)</td>
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<td>Victor A Matveev</td>
<td>(JINR Dubna)</td>
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<td>Shin-Ichi Kurokawa</td>
<td>(Tsukuba)</td>
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<td>Leandro Nisati</td>
<td>(Rome)</td>
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<td>Leonid Rivkin</td>
<td>(Lausanne)</td>
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<td>Herwig Schopper</td>
<td>(CERN) – Chair</td>
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<tr>
<td>Jurgen Schukraft</td>
<td>(CERN)</td>
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<td>Achille Stocchi</td>
<td>(LAL Orsay)</td>
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<td>John Womersley</td>
<td>(ESS)</td>
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**Co-ordination Group**

**Accelerator+Detector+Physics**

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<th>Name</th>
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<tr>
<td>Nestor Armesto</td>
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<td>Oliver Brüning – Co-Chair</td>
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<td>Stefano Forte</td>
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<td>Andrea Gaddi</td>
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<td>Erk Jensen</td>
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<td>Max Klein – Co-Chair</td>
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<td>Peter Kostka</td>
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<td>Bruce Mellado</td>
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<td>Paul Newman</td>
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<td>Daniel Schulte</td>
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<tr>
<td>Frank Zimmermann</td>
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</table>

5(11) are members of the FCC coordination team

**Working Groups**

**PDFs, QCD**
Fred Olness, Voica Radescu

**Higgs**
Uta Klein, Masahiro Kuze

**BSM**
Georges Azuelos, Monica D’Onofrio

**Top**
Olaf Behnke, Christian Schwanenberger

**eA Physics**
Nestor Armesto

**Small x**
Paul Newman, Anna Stasto

**Detector**
Alessandro Polini

**OB+MK:** FCC-eh responsibilities

**MDO:** physics co-convenor

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*We miss Guido Altarelli.*

*)February 2017
Five Major Themes of LHeC Physics

The Cleanest High Resolution Microscope of the World

The Electron Beam Upgrade of the LHC

The First High Precision Higgs Facility

Discovery Beyond the Standard Model

A Unique Nuclear Physics Facility
Five Major Themes of LHeC Physics

The Cleanest High Resolution Microscope of the World

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A Unique Nuclear Physics Facility
Resolving Proton Structure

Resolution with spectacular range (each high energy ep collider probes range down to SLAC’s 0.1fm as $Q^2$ varies) and precision:

Structure and Dynamics of

Proton, neutron, photon, pomeron, jets...

in Momentum and Transverse Space

PDFs, TMDs, DVCS, generalised PDFs, ..

presented in the LHeC CDR 1206.2913

Short version see arXiv:1211.4831

Can we continue the pass begun 60 years ago for the coming decades?

Prospect and challenge:
5 orders of magnitude in 100 years
The LHeC PDF Programme

Resolve parton structure of the proton completely: $u_v, d_v, s_v, \bar{u}, \bar{d}, s, c, b, t$ and $xg$

Unprecedented range, sub% precision, free of parameterisation assumptions, Resolve p structure, solve non linear and saturation issues, test QCD, $N^3LO$...

Note that LHC is about to reach its own limits on PDFs. $pp$ is NOT DIS, cf ATLAS $W, Z$ to 0.5%

Strong Coupling in inclusive DIS at LHeC to 0.1%

Lattice??

Jets??

BCDMS??

GUTs?

Higgs in $pp$

Note that LHC is about to reach its own limits on PDFs. $pp$ is NOT DIS, cf ATLAS $W, Z$ to 0.5%
Top electric charge

EDM and MDM

Anomalous t-q-y and t-g-Z

$V_{tb}$

Top spin

W-t-b

Top PDF

Top mass

Top-Higgs (1602.04670)

CP nature of ttH (1702.03426)

Just started to fully see the huge potential of top physics in ep at high energies
Five Major Themes of LHeC Physics

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The Electron Beam Upgrade of the LHC

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Discovery Beyond the Standard Model

A Unique Nuclear Physics Facility
High Precision for the LHC

Predict the Higg cross section in pp to 0.2% precision which matches the $M_H$ measurement and removes the PDF error.

Spacelike $M_W$ to 10 MeV from ep
⇒ Electroweak theory test at 0.01% !

Predict $M_W$ in pp to 2.8 MeV ⇒ Remove PDF uncertainty on $M_W$ LHC
Search Range Extension - worth the Lumi Upgrade

External, reliable input (PDFs, factorisation..) is crucial for range extension + CI interpretation

GLUON
SUSY, RPC, RPV, LQS..

QUARKS
Exotic+ Extra boson searches at high mass

Gluino Pair Production PDF Uncertainty

W^+

E. Kay & U. Klein using VRAP v0.9
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A Unique Nuclear Physics Facility
Higgs Physics with ep

- Higgs is produced via an EW process in ep collisions
  - No contamination from ggF and no pile-up
  - Precise theoretical control of the cross-section
- Superior sensitivity of ep with respect to pp in various aspects:
  - $h \rightarrow bb, cc, tautau$ couplings, unique access to WW-H-WW
    - Access to $h \rightarrow gg$?
  - Structure of $hVV$ and top Yukawa couplings
- Access to $hh$ and invisible decays (dark matter) in ep collisions
- Removal of QCD uncertainties to $gg \rightarrow H$ calculation for LHC
- LHC can be transformed into a high precision Higgs facility.
Five Major Themes of LHeC Physics

The Cleanest High Resolution Microscope of the World

The Electron Beam Upgrade of the LHC

The First High Precision Higgs Facility

Discovery Beyond the Standard Model

A Unique Nuclear Physics Facility
Possible Discoveries Beyond SM with LHeC

Search for Sterile Neutrinos (LHC LHeC)

- **QCD:**
  - No saturation
  - BFKL
  - Instantons
  - Higher symmetry embedding QCD

- **Electroweak:**
  - EFTs
  - Exotic Higgs Decays
  - Extension of Higgs Sector

Sterile Neutrinos …

It is a wasted p that does NOT collide with an e beam
( Oliver Fischer - 2017)

It would be a waste not to exploit the 7 TeV beams for ep and eA physics at some stage during the LHC time  (Guido Altarelli – 2008)
Five Major Themes of LHeC Physics

The Cleanest High Resolution Microscope of the World

The Electron Beam Upgrade of the LHC

The First Higgs and Top Precision Facility

Discovery Beyond the Standard Model

A Unique Nuclear Physics Facility
Electron-Ion Nuclear and Particle Physics

Extension of kinematic range in LHeC by 4 orders of magnitude: will change QCD view on nuclear structure and parton dynamics

May lead to genuine surprises...

- No saturation of $x g(x, Q^2)$?
- Small fraction of diffraction?
- Broken isospin invariance?
- Flavour dependent shadowing?

Relates to LHC Heavy Ion Physics

- Quark Gluon Plasma
- Collectivity of small nuclei (p)?
- ..

Saturation: needs large $x g$ at small $x_{ep}$ and $eA$
Design and Preparations
LHeC ERL Baseline Design

Concurrent operation to pp, LHC becomes a 3 beam facility. $P < 100\text{ MW. CW}$
### Luminosity for LHeC, HE-LHeC and FCC

<table>
<thead>
<tr>
<th>parameter [unit]</th>
<th>LHeC CDR</th>
<th>ep at HL-LHC</th>
<th>ep at HE-LHC</th>
<th>FCC-he</th>
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<tr>
<td>$E_p$ [TeV]</td>
<td>7</td>
<td>7</td>
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<td>$E_e$ [GeV]</td>
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<td>$\sqrt{s}$ [TeV]</td>
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<td>bunch spacing [ns]</td>
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<td>protons per bunch [$10^{11}$]</td>
<td>1.7</td>
<td>2.2</td>
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<td>$\gamma\epsilon_p$ [$\mu$m]</td>
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<td>electrons per bunch [$10^9$]</td>
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<td>electron current [mA]</td>
<td>6.4</td>
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<td>IP beta function $\beta^*_p$ [cm]</td>
<td>10</td>
<td>7</td>
<td>10</td>
<td>15</td>
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<td>hourglass factor $H_{geom}$</td>
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<td>pinch factor $H_{b-b}$</td>
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<td>luminosity $[10^{33}\text{cm}^{-2}\text{s}^{-1}]$</td>
<td>1</td>
<td>8</td>
<td>12</td>
<td>15</td>
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Oliver Brüning¹, John Jowett¹, Max Klein¹,², Dario Pellegrini¹, Daniel Schulte¹, Frank Zimmermann¹

¹ CERN, ² University of Liverpool

April 6th, 2017
Energy – Cost – Physics – Footprint are being reinvestigated

A 9km ERL is a small add-on for the FCC Doubling the energy to 120 GeV hugely Increases cost and effort.
Civil Engineering – full design made

CDR: Evaluation of CE, analysis of ring and linac by Amber Zurich with detailed cost estimate [linac CE: 249,928 kSF..] and time: 3.5 years for underground works using 2 roadheaders and 1 TBM

More studies needed for Integration with all services (EL,CV, transport, survey etc). Geology Understanding vibration risks Environmental impact assessment

Tunnel connection in IP2

J.Osborne et al.
The LHeC – Science + Status


PERLE CDR subm to JPhysG
Powerful ERL for Experiments (ep.yp): PERLE at Orsay

PERLE at Orsay: New Collaboration: BINP, CERN, Daresbury/Liverpool, Jlab, Orsay + CDR publication imminent.

3 turns, 2 Linacs, 15mA, 802 MHz ERL facility
-Demonstrator of LHeC
-Technology (SCRF) Development Facility
-Low E electron and photon beam physics
-High intensity: 100 x ELI

See https://indico.lal.in2p3.fr/event/3428/
H$\rightarrow$ bb in LHeC Detector
Installation Study
2 years (in LS4)

Detector fits in L3 magnet support

Modular structure

LHeC INSTALLATION SCHEDULE

<table>
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<tr>
<th>ACTIVITY</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
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<td>DETECTOR CONSTRUCTION ON SITE TO START BEFORE LHC LONG SHUT-DOWN</td>
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<td>COIL COMMISSIONING ON SURFACE</td>
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<td>LOWERING TO CAVERN</td>
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<td>CABLES &amp; SERVICES</td>
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<td>ENDCAPS MUON CHAMBERS</td>
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<td>LHC LONG SHUTDOWN END (T0+24m)</td>
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“The future belongs to those who believe in the beauty of their dreams.”

Anna Eleanor Roosevelt
(1884-1962)

Universal Declaration of Human Rights (1948)

cited by Frank Zimmermann at the FCC Meeting at Washington DC, March 2015
CERN can do pp and lp: in the 80ies it successfully did

UA1

UA2

Pierre Darriulat
now in Vietnam

“ We have two tasks: kill Weinberg Salam, kill QCD”
Carlo Rubbia: 1978 BCDMS meeting at Dubna.
The failure to fulfill his task made Carlo famous…

Charged Currents

BEBC, CDHS(W), CHARM, CHORUS

Neutral Currents

BCDMS, EMC, SMC, COMPASS
In agreement with DG we Work on an update of the LHeC CDR as input to Euro Strategy. We find it is worth it the deeper we look.

We’d be glad to have many of you with us.
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